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# Laboratory Investigation and Characterization of Some Coal Combustion Byproducts for their Effective Utilization

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## *Abstract*

Thermal power stations use pulverized coal as fuel. They produce enormous quantities of coal ash as a by-product of combustion. This calls for the development of strategies to encourage and establish technological concepts which will ensure consumption of fly ash in bulk. This paper presents a review of some of the experimental studies carried out in the laboratory. The purpose is to find out a suitable utilization avenue for a particular fly ash sample depending upon its physical, chemical, morphological and engineering properties and thus reduce the need for vast areas for disposal of fly ash which in turn causes considerable damage to the environment. Some of the experiments which are conducted are particle size analysis, specific gravity, wet density, specific surface area, moisture content, turbidity, X-ray diffraction (XRD) studies, Scanning Electron Microscopy (SEM) studies, Energy-dispersive X-ray spectroscopy (EDX) studies. Based on the results obtained from these experiments, suitable end use for the fly ash based on the characteristics of the samples is ascertained.

## 1.0 Introduction

Coal-based thermal power plants all over the world face serious problems of handling and disposal of the ash produced. The high ash content (35–55%) of the coal in India makes this problem more complex. At present, about 85 thermal power stations produce nearly 118 million tones of coal ash per annum and it is estimated that the coal ash production will reach 175 million tones by 2012 and may exceed 225 million tones by 2017 A.D (Kumar 2006, pp.191-199). Safe disposal of the coal ash without adversely affecting the environment and the large storage area required are major concerns of thermal power plants. Hence attempts are being made to utilize the ash rather than dump it in the vicinity of the power plants in the ash ponds. The coal ash can be utilized in bulk only in geotechnical engineering applications such as construction of embankments, as a backfill material, as a sub-base material, etc. For this, an in-depth understanding of the physical and chemical properties, and engineering and leaching behavior are required. This paper reports the little work which is being carried out in this context for bulk utilization of fly ash in various fields of engineering applications. This will call for a proper handling, disposal and utilization of the coal ash being disposed of in huge quantity. However, the quantity and the quality of the ash produced mainly depends upon the quality of the coal used, its pulverization, combustion technique adopted, operation of the boiler units, type of collection system employed, etc. (Singh et al. 2002, pp.267-299). These factors may also cause characteristics of the ash to vary, invariably, from one plant to another, and sometimes even at the same power plant. As such, efficient utilization of the coal ash becomes a very challenging task, which should be based on its physical, chemical and mineralogical characterization (Joshi et al.1975, pp.791-806). At present only 30-35% of the ash disposed is being used for various purposes viz. as a stabilizer of sub-grade (Pandian 2004, pp. 189-216) and sub-bases in pavement construction (Sridharan et al. 1996, pp. 97-110), as a filler material for mines (Pandey and Kumbhakar 2007, pp. 23-27), as a material for construction of roads and embankments (Murthy 1996, pp. 222-237 and Bumzoo et al. 2005, pp. 914-924), as a structural fill (DiGioia and Nuzzo, 1997 pp. 77-99 and Leonards and Bailey 1982, pp. 517-531). In these studies, it has been demonstrated that the coal ash properties can be improved with addition of lime, cement and other chemicals. However, efforts are lacking in demonstrating the potential of the coal ash as a man made resource which can be used for different engineering applications. Such studies would be of great help in making a judicious choice for ash utilization and evolving a methodology to work out the finer details for the same.

## 2.0 Basic considerations

The coal ash, which includes both fly ash and the bottom ash (or boiler slag), and is better known as the pulverized fuel ash, is a by-product produced at thermal power plants due to the combustion of pulverized coal, with low calorific value and with high ash content. It is a pozzolana (a siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, reacts chemically with calcium hydroxide, at normal temperatures, to form compounds possessing cementitious properties). The quality of the ash produced mainly depends on the quality of coal, its pulverization, combustion technique, ash handling, and collection techniques. Physical properties help in classifying the coal ashes for engineering purposes and some are related to engineering properties. The properties discussed here are specific gravity, grain size distribution, specific surface area and wet density, chemical composition, morphological characteristics and turbidity.

## *3.0 Materials and Methods*

Fly ash samples from seven sources were collected directly from the hoppers of Electrostatic Precipitators (ESPs) in gunny bags and transported with care to the place of experimentation. The sample ID and their source of collection is given in Table-I

**Table-I: Sample ID and their source of collection**

| Sl.No. | Sample ID | Source of collection | State |
|---|---|---|---|
| 1 | RSP-CPP-II | Rourkela Steel Plant, Captive Power Plant-II | Orissa |
| 2 | OPGC | IB Thermal Power Plant, Banharpali, Jharsuguda | Orissa |
| 3 | STPP | Super Thermal Power Plant, NTPC, Kanhia, Angul | Orissa |
| 4 | PTPS | Patratu Thermal Power Plant, Ranchi | Jharkhand |
| 5 | ETPS | Ennore Thermal Power Plant, Ennore | Tamilinadu |
| 6 | NALCOCPP | National Aluminium Company, Angul | Orissa |
| 7 | TTPS | Talcher Thermal Power Plant, NTPC, Talcher | Orissa |

The following tests were conducted on the oven-dried fly ash samples in the laboratory.

### *3.1. Mineralogical characterization*

#### *3.1.1. X-ray diffraction (XRD) analysis*

The ash samples were evaluated for its mineralogical composition by conducting XRD Spectrometer (Philips Analytical X-ray B.V., X'Pert Graphics & Identify, York Street, Cambridge) studies, using a graphite monochromator and Cu Kα radiation. The ash samples were scanned for 2θ angle ranging from 5 to $80^0$. These studies are carried out primarily to identify the mineral phases. The studies carried out by various investigators indicate that coal ashes predominantly consist of quartz and feldspar minerals. Sahu (1991) reported that the nature and properties of the minerals mainly depend upon the source of coal. The process of ashification in turn controls the grain fusion, grain morphology as well as crystal growth.

#### *3.1.2. Scanning Electron Microscopy (SEM) studies*

These studies were conducted to determine the morphology of the ash particles. A SEM (JEOL JSM 6480 LV, Japan) was used to conduct these studies. SEM studies are carried out to have a closer view of the individual particles of coal ashes. Investigations carried out by Pandian et al. (1998) show that the coal ash particles are generally cenospheres, leading to low values of specific gravity.

### *3.2. Chemical characterization*

The chemical properties of the coal ashes mainly influence the environmental impacts that may arise out of their use/disposal as well as their engineering properties. The adverse impacts include contamination of surface and subsurface water with toxic heavy metals present in the coal ashes, loss of soil fertility around the plant sites, etc. Thus a detailed study of the chemical composition, morphological studies, pH, total soluble solids etc. is necessary. Chemical composition also suggests the possible areas of application of coal ash. Roode (1987) reported that loss on ignition is generally equal to the carbon content. Throne and Watt (1965) observed that the amount of $SiO_2$ or $SiO_2 + Al_2O_3$ in fly ash influences the pozzolanic activity. Minnick (1959) has reported that a relatively high percentage of carbon decreases the pozzolanic activity. The Indian fly ashes contain silica, alumina, iron oxide and calcium oxide. The silica content in fly ashes ranges between 38 to 63%, the alumina content ranges between 27 and 44%, the calcium oxide is in the range of 0 to 8%. It has been found that all the Indian coal ashes satisfy the chemical requirements for use as a pozzolana. According to ASTM 618 classification, only Neyveli fly ash can be classified as Class C fly ash and all other fly ashes fall under Class F.

#### *3.2.1. Energy-dispersive X-ray spectroscopy (EDX) studies*

The chemical composition, calculated as major oxides, of the ash samples are obtained with the help of an EDX set-up (JEOL JSM 6480 LV, Japan). EDX is a technique used for identifying the elemental composition of the specimen. The EDX analysis system works as an integral feature of a Scanning Electron Microscope (SEM) and can not operate on its own without the latter. It is an analytical tool predominantly used for chemical characterization. Being a type of spectroscopy, it relies on the investigation of a sample through interactions between light and matter, analyzing X-rays in its particular case. Its characterization capabilities are due in large part to the fundamental principle that each element of the periodic table has a unique electronic structure and, thus, a unique response to electromagnetic waves. Spectroscopy data is often portrayed as a graph plotting counts vs. energy. The peaks correspond to characteristic elemental emissions. The release of X-rays creates spectral lines that are highly specific to individual elements; thus, the X-ray emission data can be analyzed to characterize the sample in question.

### *3.3 Physical characterization*

### *3.3.1 Specific gravity*

The specific gravity of the ash samples were determined using a stoppered bottle having a capacity of 50 ml as per the guidelines provided by the American Society of Testing Materials (ASTM D 854). For the sake of accuracy, the average specific gravity is obtained from the results of five tests. Specific gravity is one of the important physical properties needed for the use of coal ashes for geotechnical and other applications. In general, the specific gravity of coal ash is around 2.0 but can vary to a large extent (ranging from 1.6 to 3.1). Because of the generally low value of the specific gravity of coal ashes compared to soils, ash fills tend to result in low dry densities. The reduction in unit weight is of advantage in the case of its use as a backfill material for retaining walls since the pressure exerted on the retaining structure as well as the foundation structure will be less. The other application areas which can get benefit of low density include embankments especially on weak foundation soils, reclamation of low-lying areas, etc. The variation of specific gravity of the coal ash is the result of a combination of many factors such as gradation, particle shape and chemical composition. It is known that coal ash comprises mostly glassy cenospheres and some solid spheres. The reason for a low specific gravity could either be due to the presence of large number of hollow cenospheres from which the entrapped air cannot be removed, or the variation in the chemical composition, in particular iron content, or both.

### *3.3.2 Specific surface area*

The specific surface area of the ash samples were determined by using a Blaine's apparatus (ASTM C 204) with Portland cement as a standard reference material. For calculating the specific surface area of the ash samples, the following equation was used:

$$\text{Specific surface area (cm}^2\text{/g)}, \quad S = \{S_s\,(1-e_s)\,\sqrt{e^3}\sqrt{T}\} \,/\, \{\sqrt{e_s^3}\sqrt{T_s}\,(1-e)\}$$

Where S is the specific surface area of the ash sample, $S_s$ the specific surface area of the Portland cement (3460 $cm^2/g$), e the void ratio of the ash sample, $e_s$ the void ratio of the cement (=0.5), $T_s$ the measured time interval of manometer drop, for cement (77.18s) and T is the measured time interval of manometer drop for ash sample. The study of specific surface of soils is widely recognized as a means to understand their physical and engineering behavior. Even though coal ashes are primarily silt/sand-sized particles and their specific surface is expected to be very low, results need to be obtained for completeness and for use in certain cases.

### *3.3.3 Particle size analysis*

The gradational properties of the ash samples are obtained by using Malvern particle size analyzer (UK). Soft imaging system has also been used to determine the grain-size distribution characteristics of the ash samples by using Mastersizer 2000 version 5.22. Grain size distribution indicates if a material is well graded, poorly graded, fine or coarse, etc. and also helps in classifying the coal ashes. Coal ashes are predominantly silt sized with some sand-size fraction. Leonards and Bailey (1982) have reported the range of gradation for fly ashes and bottom ashes which can be classified as silty sands or sandy silts. The pond ashes consist of silt-size fraction with some sand-size fraction. The bottom ashes are coarser particles consisting predominantly of sand-size fraction with some silt-size fraction. Based on the grain-size distribution, the coal ashes can be classified as sandy silt to silty sand. They are poorly graded with coefficient of curvature ranging between 0.61 and 3.70. The coefficient of uniformity is in the range of 1.59–14.0.

## *4.0 Results and discussions*

Results of various experiments conducted in the laboratory on the fly ash samples are presented as follows:

### 4.1 Mineralogical characterization

#### 4.1.1 Scanning Electron Microscopy (SEM) studies

The SEM studies on the fly ash samples, indicate presence of particles with different shapes viz. spherical, hollow (cenosphere), broken, plerosphere (i.e. a sphere within another sphere), tubular and some other irregular shaped particles in it as shown in Fig-1 and Fig.1(a). It can be noticed from SEM photomicrographs of fly ash samples that due to the alkali activation, some overgrowth on the surface of the ash particles takes place as evidenced from PTPS and TTPS fly ash photomicrographs which further leads to the agglomeration of ash particles.

**Fig-1: SEM Photomicrographs of fly ash samples at 5000 magnification**

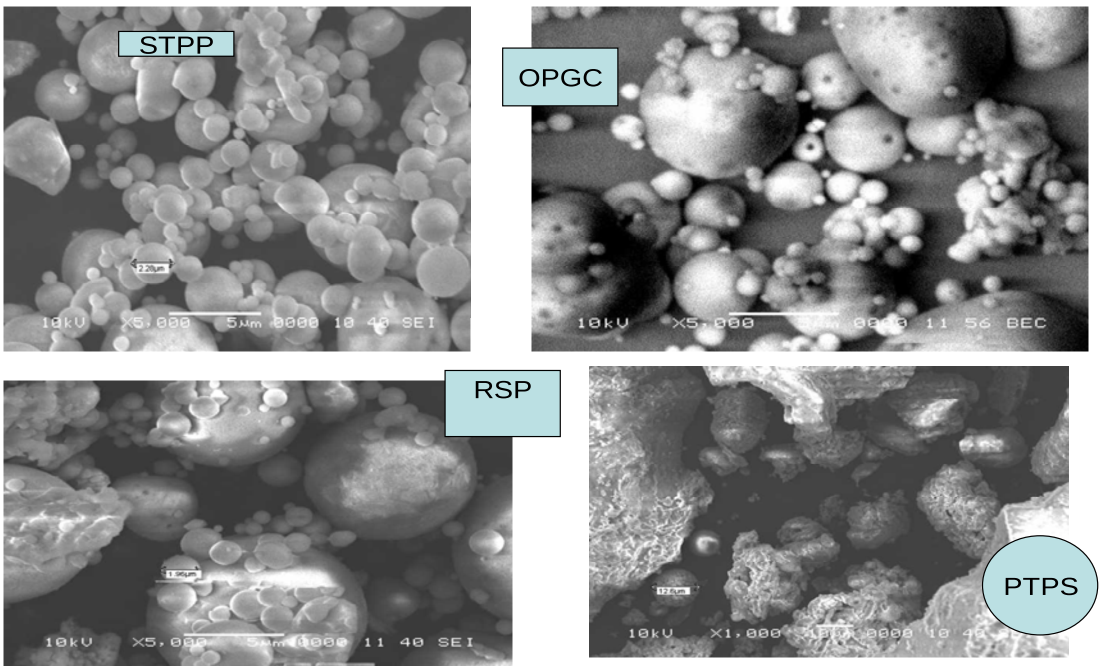
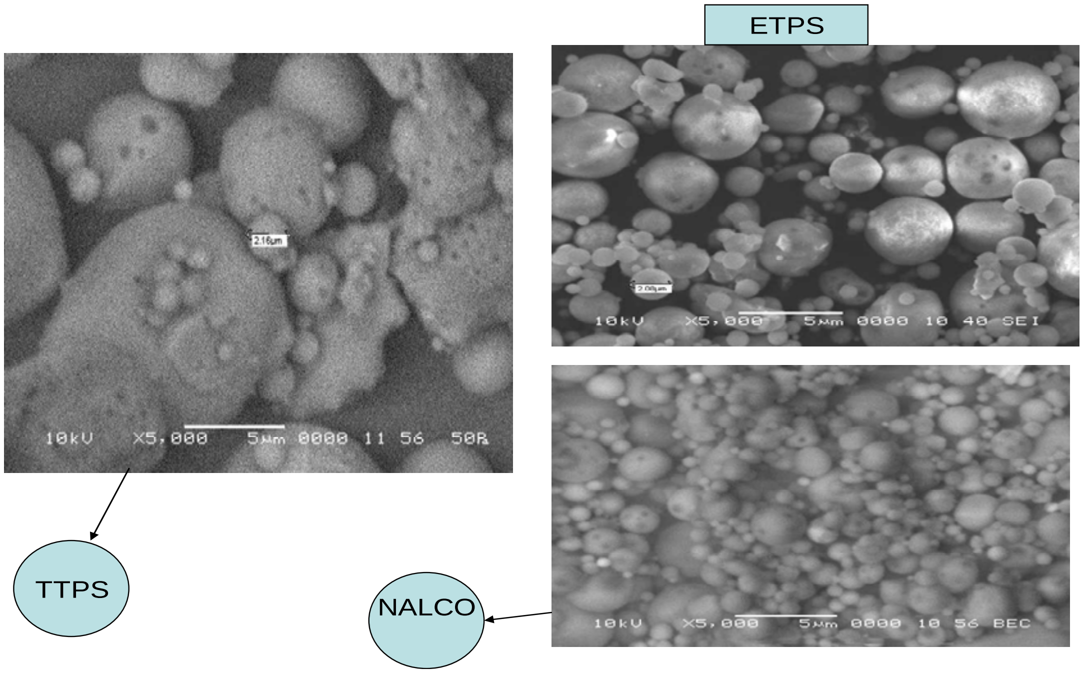


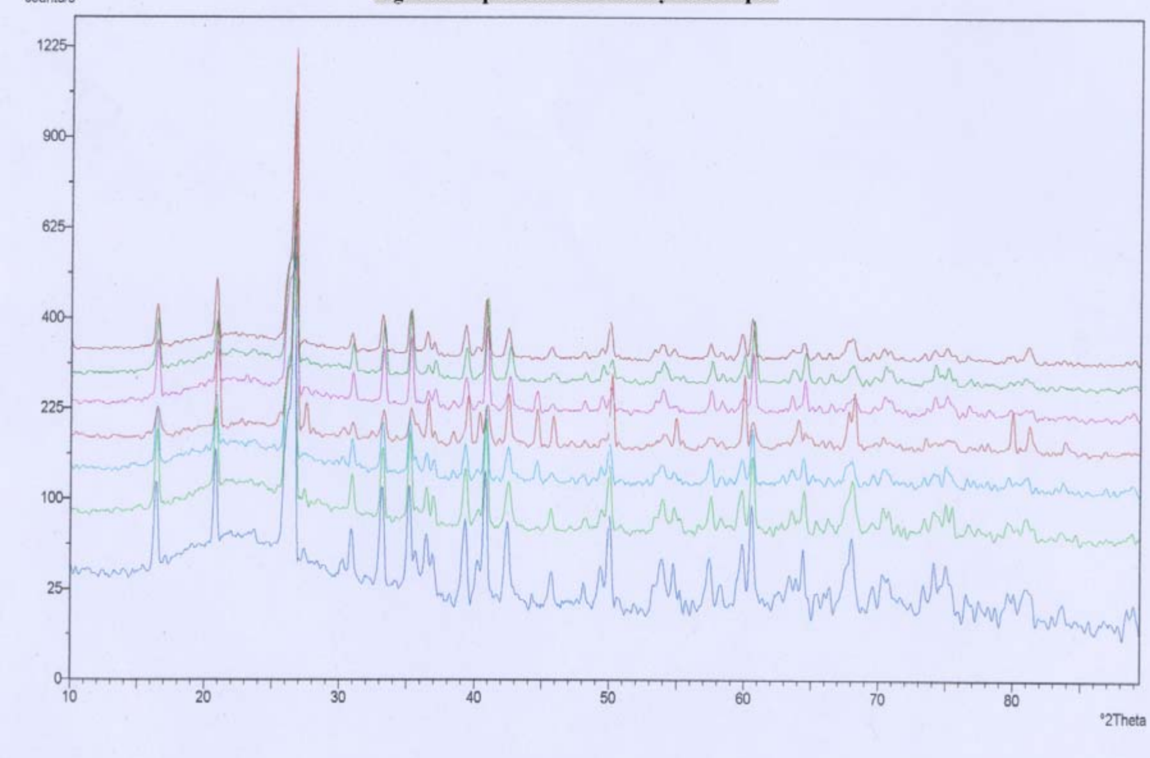
Fig-1(a): SEM Photomicrographs of fly ash samples at 5000 magnification




### *4.1.2 X-ray diffraction (XRD) analysis*

The XRD patterns of the various fly ash samples are presented in Fig-2. It can be noticed from the XRD patterns that the fly ash samples consist predominantly of the crystalline phases quartz, mullite, hematite and magnetite in a matrix of aluminosilicate glass.

Fig.2: XRD patterns for seven fly ash samples




### *4.2. Chemical characterization*

#### *4.2.1. Energy-dispersive X-ray spectroscopy (EDX) studies*

The chemical composition (by % weight) of the fly ash samples is presented in Table-I. It can be observed from the table that the major constituents of these samples are; silica ($SiO_2$), alumina ($Al_2O_3$) and ferric oxide ($Fe_2O_3$). Minor quantities of calcium oxide (CaO), magnesium oxide (MgO), sodium oxide ($Na_2O$), potassium oxide ($K_2O$), rutile ($TiO_2$) and other compounds are also observed to be present in lesser quantity which are not shown in the table. These results indicate that all the seven fly ash samples tested belong to CLASS 'F' as per ASTM 618 specification.

**Table-I: Chemical composition of fly ashes studied**

| Sample ID | Elements (weight %) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $K_2O$ | $TiO_2$ | $Na_2O$ | MgO |
| ETPS | 56.77 | 31.83 | 2.82 | 0.78 | 1.96 | 2.77 | 0.68 | 2.39 |
| NALCOCPP | 59.15 | 34.80 | 3.52 | 0.76 | 2.62 | 1.14 | 0.05 | 0.05 |
| OPGC | 59.64 | 35.60 | 0.86 | 0.85 | 1.86 | 0.91 | 0.06 | 0.67 |
| PTPS | 78.48 | 22.90 | 0.15 | 0.36 | 0.91 | 1.46 | 0.03 | 0.06 |
| RSPCPP-II | 62.41 | 31.65 | 0.17 | 2.19 | 2.63 | 0.00 | 3.42 | 0.08 |
| STPP | 62.25 | 30.47 | 2.48 | 1.92 | 1.39 | 0.58 | 0.02 | 1.90 |
| TTPS | 61.46 | 36.95 | 0.59 | 2.02 | 2.01 | 0.31 | 0.07 | 0.26 |

#### *4.2.2 Specific gravity*

A series of tests are conducted to determine the specific gravity of the fly ash samples. The average values of specific gravity of the fly ash samples are summarized in Table-II. These values ranged from 1.91 to 2.43, indicating a large variation between ash sources. As reported by Bumjoo et al. (2005), the wide range in specific gravity can be attributed to two factors: (1)

chemical composition, and (2) presence of hollow fly ash particles. The low specific gravity of RSPCPP-II and OPGC fly ashes are explained by their low iron oxide contents and, conversely, the high specific gravity of NALCOCPP fly ash by its high iron oxide content. Different amounts of hollow particles present in fly ash also cause a variation in apparent specific gravity. Obviously, a fly ash containing a large percentage of hollow particles would have a lower apparent specific gravity than one with mostly solid particles. In fact, the two factors affecting the specific gravity of the fly ash may be related to each other. Guo et al. (1996) examined the chemical compositions of hollow and solid fly ash particles separately, and the data revealed that hollow-particle fly ash had significantly lower iron content (4.5%) than solid- particle fly ash (25%).

#### *4.2.3 Specific surface area*

The specific surface area of the fly ash samples are also presented in Table-II. It is revealed from the table that it varies between 0.187 $m^2$/gram-1.240 $m^2$/gram.

**Table-II: Physical properties of fly ash samples investigated**

| Sample ID | Specific gravity | Specific surface area ($m^2$/gram) | Moisture content (%) | Wet density (gram/cc) | Turbidity (NTU) |
|---|---|---|---|---|---|
| ETPS | 2.20 | 1.240 | 0.200 | 1.75 | 459 |
| NALCOCPP | 2.43 | 1.190 | 0.797 | 1.60 | 397 |
| OPGC | 1.98 | 0.458 | 0.250 | 1.67 | 456 |
| PTPS | 2.35 | 0.187 | 0.150 | 1.89 | 389 |
| RSPCPP-II | 1.91 | 0.458 | 0.398 | 1.95 | 345 |
| STPP | 2.19 | 0.428 | 0.219 | 1.99 | 458 |
| TTPS | 2.21 | 0.395 | 0.401 | 1.80 | 428 |

#### *4.2.4. Particle size analysis*

Particle size analysis has been performed for the seven fly ash samples. The results are given in Table-III. Although, the obtained results cannot be compared easily, the grain size distributions for the fly ash samples indicate that the fly ash samples consist of sand-sized (<4.75 mm), silt-sized (0.075-0.002 mm) and clay-sized (<0.002 mm) particles. From the table it can be seen that the ash samples are almost uniformly graded. It is also observed that majority of particles in ETPS, NALCOCPP, OPGC, RSPCPP-II and TTPS fly ash samples are less than 50 µm size. Only one sample i.e. PTPS fly ash has majority particles more than 50 µm size, hence more amenable for geotechnical applications.

**Table-III: Results of Particle size Analysis of fly ash samples investigated**

| Sample ID | Size range (%) | | | Uniformity Co-efficient, $C_u$ |
|---|---|---|---|---|
| | ‹ **1** µm | 1 µm - 50 µm | › 50 µm | |
| ETPS | 3.66 | 87.80 | 08.54 | 2.32 |
| NALCO-CPP | 2.77 | 92.73 | 04.50 | 1.15 |
| OPGC | 1.02 | 68.20 | 30.78 | 1.12 |
| PTPS | 0.10 | 34.37 | 65.53 | 0.70 |
| RSP-CPP-II | 1.02 | 68.40 | 30.58 | 1.12 |
| STPP | 0.97 | 58.07 | 40.96 | 1.09 |
| TTPS | 0.90 | 55.16 | 43.94 | 1.07 |

## 5.0 Conclusions

The present work is an attempt to study the various characteristics of fly ash samples investigated from seven thermal power plants situated in various parts of the country. It is believed that for bulk utilization of these fly ashes, in particular, as a fill material, these investigations are of great importance. Based on the experimental investigations conducted in the present study, on the fly ash samples, the following conclusions can be drawn:

►From the SEM studies, it is clear that agglomeration of fine particles takes place, due to alkali activation of the fly ash.

►The alkali activation of the fly ash samples result in its specific gravity ranging from 1.91 to 2.43

►The specific surface area of the fly ash samples is noticed to range between 0.187 $m^2$/gram to1.240 $m^2$/gram.

►From the grain size distribution curve it is seen that the fly ash samples are well graded.

## 6.0 Concluding remarks

A variety of tests were performed on fly ashes composed of fine, nearly spherical particles ranging in size from silt to fine sands. These fly ashes exhibit some morphological characteristics that are distinctly different from typical soils. The fly ash particles in this study were mostly hollow spheres with thin walls. Also, some of the fly ash particles were agglomerations of finer particles. The morphological characteristics of fly ash have affected their specific gravity to varying degree. Based on the results obtained in this study it appears that fly ashes are suitable for use in highway embankments, if proper design and construction procedures are followed. Prior to use, the materials must pass the appropriate environmental requirements set by state regulatory agencies. If the environmental requirements are satisfied, the fly ashes can provide fill materials to most soils, while having the advantage of smaller specific gravity. In nutshell, the present study reveals that fly ash can be used as a fill material for the reclamation of low lying wastelands, refuse dumps and filling of mine voids. The investigations carried out on fly ashes show that they have the good potential for use in geotechnical applications as well. Its low specific gravity, insensitiveness to changes in moisture content, etc. can be gainfully exploited in the construction of embankments, roads, reclamation of low-lying areas, fill behind retaining structures, etc.

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